Polarization Anomaly in $B \to \phi K^*$ and Probe of Tensor Interactions

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Abstract

The pure penguin process $B \to \phi K^*$ is one of the most important probes of physics beyond the Standard Model. Recently BaBar and Belle have measured the unexpectedly large transverse polarization in the decays $B \to \phi K^*$, which may single out new physics effects beyond the Standard model. We study the possibility that the phenomenon could serve as an important probe of anomalous tensor interactions. We find that a spin flipped tensor interaction with a small strength and a phase could give a possible solution to the polarization puzzle.

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Looking for signals of physics beyond the Standard Model is one of the most important missions of high energy physics. It is well known that flavor-changing neutral currents induced in B decays are one of the best probes of new physics beyond the Standard Model because they arise only through loop effects in the Standard Model (SM). To this end, the decays $B \to \phi K^*$ are of particular interests, since they are pure penguin processes and have interesting polarization phenomena as well as relatively clear experiment signature. Within the SM, it is expected that both ϕ and K^* are mainly longitudinally polarized, while its transverse polarization is suppressed by the power of $m_{\phi,K^*}/m_B$. However, last year both BaBar and Belle had observed rather small longitudinal polarizations in the decays

$$f_L(\phi K^{*+}) = 0.46 \pm 0.12 \pm 0.03 \,, \quad f_L(\phi K^{*0}) = 0.65 \pm 0.07 \pm 0.02 \quad \text{(BaBar [1])}, \tag{1}$$

$$f_L(\phi K^{*0}) = 0.43 \pm 0.09 \pm 0.04 \,, \quad f_T(\phi K^{*0}) = 0.41 \pm 0.10 \pm 0.04 \quad \text{(Belle [2])}. \tag{2}$$

Due to $|f_0| + |f_T| = 1$, both groups have measured unexpectedly large transverse polarizations in the $B \to \phi K^*$ decays.

This summer BaBar Collaboration has again reported their full angular analysis of the the decay $B^0 \to \phi K^*$ [3]

$$f_L(\phi K^{*0}) = 0.52 \pm 0.05 \pm 0.02 \,, \quad f_T(\phi K^{*0}) = 0.22 \pm 0.05 \pm 0.02 \,, \tag{3}$$

which has confirmed their previous measurements and called urgent theoretical explanations.

The final states ϕ and K^* are fast moving in the B meson frame and any spin flip of fast flying quark will be suppressed by power of m_q/E. The charge interaction currents structure of the SM is left-handed, therefore, will result in the dominance of longitudinal polarization. Such situation has been known to us for many years [4, 5, 6]. So that, the recent measurements of large transverse polarizations in $B \to \phi K^*$ are referred as a puzzle within the high energy physics community [7].

The analysis of the decays within the SM can be performed in terms of an effective low-energy theory with the Hamiltonian [8]

$$\mathcal{H}_{\rm eff}^{\rm SM} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=3}^{10} C_i O_i \,. \tag{4}$$

The amplitude for the decay within the SM can be written as

$$\mathcal{A}_{\lambda\lambda} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* a(\phi K^*) \langle \phi | \bar{s} \gamma_\mu s | 0 \rangle \langle K^* | \bar{s} \gamma^\mu (1-\gamma_5) b | B \rangle$$

$$
\begin{aligned}
&= \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* a(\phi K^*) i f_\phi m_\phi \left[\varepsilon_1^* \cdot \varepsilon_2^* (M_B + M_{K^*}) A_1(m_\phi^2) \right. \\
&\quad \left. -(\varepsilon_1^* \cdot P_B)(\varepsilon_2^* \cdot P_B) \frac{2A_2(m_\phi^2)}{M_B + M_{K^*}} + i\epsilon_{\mu\nu\alpha\beta} \varepsilon_2^{*\mu} \varepsilon_1^{*\nu} P_B^\alpha P_{K^*}^\sigma \frac{2V(m_\phi^2)}{M_B + M_{K^*}} \right] . \qquad (5)
\end{aligned}
$$

Since B meson is a pseudoscalar, the final two vector mesons must have the same helicity. In the helicity basis, the amplitude can be decomposed into three helicity amplitudes, which are

$$
\begin{aligned}
H_{00} &= \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* a(\phi K^*) \frac{i f_\phi}{2M_{K^*}} \left[(M_B^2 - M_{K^*}^2 - M_\phi^2)(M_B + M_{K^*}) A_1 - \frac{4 M_B^2 p_c^2 A_2}{M_B + M_{K^*}} \right] , \\
H_{\pm\pm} &= i \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* a(\phi K^*) M_\phi f_\phi \left[(M_B + M_{K^*}) A_1 \mp \frac{2 M_B p_c}{M_B + M_{K^*}} V \right] . \qquad (6)
\end{aligned}
$$

In naive factorization [9],

$$
a(\phi K^*) = a_3 + a_4 + a_5 - \frac{1}{2}(a_7 + a_9 + a_{10}) .
$$

Then the branching ratio is thus read as

$$
\mathcal{B} = \frac{\tau_B p_c}{8\pi M_B^2} \left(|H_0|^2 + |H_+|^2 |H_-|^2 \right) . \qquad (7)
$$

And the longitudinal and the transverse polarization rates are

$$
f_L = \frac{\Gamma_L}{\Gamma} = \frac{|H_0|^2}{|H_0|^2 + |H_+|^2 |H_-|^2} , \quad f_T = \frac{\Gamma_T}{\Gamma} = \frac{|H_+|^2 + |H_-|^2}{|H_0|^2 + |H_+|^2 + |H_-|^2} . \qquad (8)
$$

Using the Wilson coefficients c_{3-6} evaluated at scale of $\mu = m_b$ [8], and the decay constants $f_B = 0.18$ GeV, $f_\phi = 0.221$ GeV and the form factors of light-cone QCD sum-rules [11], one can get

$$
\mathcal{B}(B \to \phi K^*) \sim 8.55 \times 10^{-6} , \quad f_L \sim 0.90 , \quad f_T \sim 0.09 .
$$

It must be reminded that a theoretical estimation of the branching ratios depend very strongly on the form factors from different hadronic models and the theoretical frameworks of B meson nonletponic decays, even though most frameworks and form factors predict dominance of the longitudinal polarizations. For example, recent calculation of $Br(B^0 \to \phi K^{*0})$ by Cheng and Yang by using QCD factorization [10] gives $Br \sim 8.71 \times 10^{-6}$ for LCSR and 4.62×10^{-6} for BSW form-factors [11, 12], respectively, while pQCD [13] calculation gives $Br \sim 14.86 \times 10^{-6}$ where form-factors are not inputs. However, both studies present the dominance of longitudinal polarization.

After BaBar and Belle measurements of the abnormal large transverse polarization, there have been some theoretical explanations; namely, through the final state interactions (FSI) contributions [14], large annihilation contributions and new physics from right-hand current interactions [15] and transverse ϕ from the emitted gluon of $b \to sg^*$ which might be enhanced by new physics [16].

In this letter, we investigate the possibility that the abnormally large transverse polarization may arise from a new tensor interaction beyond the SM (bSM),

$$\mathcal{H}_{\rm eff}^{\rm bSM} = \frac{G_F}{\sqrt{2}} |V_{ts}| g_{_T} e^{i\delta_T} \bar{s}\sigma_{\mu\nu}(1+\gamma_5)s \otimes \bar{s}\sigma^{\mu\nu}(1+\gamma^5)b \ , \tag{9}$$

where $g_{_T}$ is the relative interaction strength normalized to that of $b \to s\bar{s}s$ in the SM and $i\delta_T$ is the new physics phase. In principle, such a tensor operator could be produced even in MSSM [17, 18]. Interestingly, the recent study of radiative pion decay $\pi^+ \to e^+\nu\gamma$ at PIBETA [19] has found deviations from the SM in the high-E_γ kinematic region, which may indicate the existence of a tensor quark-lepton interaction [20, 21]. We also note that Kagan mentioned the case of tensor operator for resolving the puzzle [15].

Our starting point arises from the observation that the tensor interaction only contributes to transverse polarization but not to longitudinal one. The matrix element reads [11]

$$\langle \phi(q, \epsilon^{T*}) | \bar{s}\sigma_{\mu\nu}s|0\rangle = -i f_\phi^T (\epsilon_\mu^{T*} q_\nu - q_\mu \epsilon_\nu^{T*}) \ , \tag{10}$$

which is scaled as $f^T E_\phi$ since $q \sim E_\phi(1,0,0,1)$ for fast flying ϕ. However, if the ϕ meson is produced instead from a vector interaction vertex, we will have $\langle \phi(q,\epsilon)|\bar{s}\gamma_\mu s|0\rangle = f_\phi m_\phi \epsilon_\mu^*$, and it is easy to understand that the longitudinal polarization dominate over the transverse one by a large factor m_B/m_ϕ because of $\epsilon_L^\mu \to q^\mu/m_\phi$.

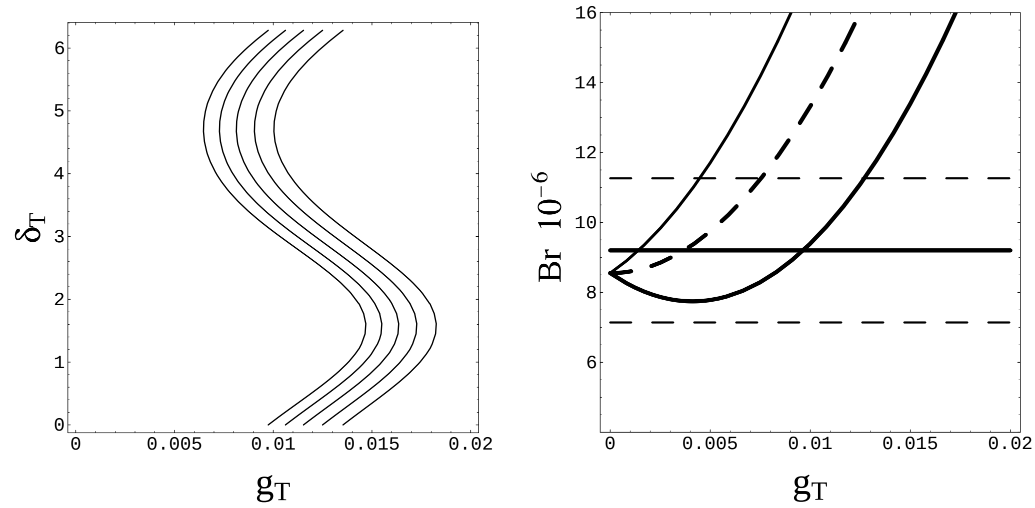
Using the form factors defined in Ref. [11], we can write down the amplitude of the tensor operator in Eq. (9) in naive factorization approximation,

$$\begin{aligned}\langle \phi(q) K^*(p) | \mathcal{H}_{eff}^T | B(p_B)\rangle = \frac{G_F}{\sqrt{2}} |V_{ts}| g_T e^{i\delta_T} (-2i f_\phi^T) \times \\ \{\epsilon_\phi^{T*} \cdot \epsilon_{K^*}^{T*} T_2(m_\phi^2)(m_B^2 - m_{K^*}^2) + 2i T_1(m_\phi^2) \varepsilon_{\mu\nu\alpha\beta} \epsilon_\phi^{T*\mu} \epsilon_{K^*}^{T*\nu} p_B^\alpha p^\beta\} \ .\end{aligned} \tag{11}$$

From this equation, we can get the new physics contributions,

$$H_{00}^{\rm bSM} = 0 \ , \tag{12}$$

$$H_{\pm\pm}^{\rm bSM} = \frac{G_F}{\sqrt{2}} |V_{ts}| g_{_T} e^{i\delta_T} (-2i f_\phi^T) \left[(m_B^2 - m_{K^*}^2) T_2(m_\phi^2) \mp 2 m_B p_c T_1(m_\phi^2)\right] \ . \tag{13}$$



(a) (b)

Figure 1: (a) The contour plot for $f_L = 0.52 \pm 0.05 \pm 0.002$ within 2σ. The central curve is for the center value of f_L, and the nearby curves are for f_L at 1σ, 2σ variances, respectively. (b) The branching ratio constraints: The thin curve, the dashed curve and the thick curve are for $\delta_T = 3\pi/2,\ \pi,\ \pi/2$, respectively. The horizontal lines are the experimental results for $Br(B^0 \to \phi K^*)$ with 2σ variance.

Compared with Eq.9, the tensor interaction contributions to $H_{\pm\pm}$ are enhanced by a factor of M_B/m_ϕ.

Numerical results are presented in Fig. 1. From Fig. 1(a), we can find that the transverse polarization in $B^0 \to \phi K^{*0}$ is very sensitive to the presence of new tensor interactions. For $0.005 < g_T < 0.02$, we can easily find solutions to the polarization puzzle depending on the phase of the tensor interaction. For example, to account for $f_L = 0.52 \pm 0.05 \pm 0.002$ within 2σ, we get intervals $g_T \in (0.014, 0.019)$, $(0.009, 0.015)$, $(0.006, 0.011)$ for $\delta_T = \pi/2, \pi, 3\pi/2$, respectively. Of course, the branching ratio measurements could also give constraints on such a tensor interaction operator, which are presented in Fig. 1(b). Here we can see the windows are very narrow because the longitudinal contribution estimated within the SM already saturate the experimental branching ratio. However, it is well known that theoretical calculations of the branching ratios of hadronic B decays suffer from large uncertainties. It is believed that polarization fractions could be predicted more accurately than the branching ratios, because some of hadronic uncertainties could be cancelled in the former ones. In the future, if theoretical frameworks for hadronic B decays could achieve 10% accuracy and their predictions of longitudinal

branching ratio still saturate the experimental measurement, the tensor interaction scenario could be ruled out. In such a case, we need not only new physics contributions to transverse part but also new contributions destructive to longitudinal part. However, it would be very hard to account for the large branching ratio of $B \to \phi K$ because the similarity between the amplitudes of $B \to \phi K$ and the longitudinal amplitude of $B \to \phi K^*$ in the heavy M_b limit.

In conclusion, we have studied the large transverse polarization puzzle in $B \to \phi K^*$ decays, which is taken as an important probe of an anomalous tensor interactions. We find that a relatively weak tensor interaction could resolve the puzzle. If we take the coupling $g_T = m_W^2/\Lambda_T^2$, such a solution might be a signal of new physics with tensor interaction at TeV scale. With the running of B factories BaBar and Belle, we have witnessed many challenging phenomena. Theoretically, we need more accurate and complete framework to clarify whether the SM could explain those abnormal phenomena or not.

Note added: When we finished our work, we note the paper[22] where the same tensor operator is also studied.

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